

The total mass and dark halo properties of the Small Magellanic Cloud

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ABSTRACT

We discuss the total mass and dark halo properties of the Small Magellanic Cloud (SMC) for reasonable V -band stellar-to-mass-to-light ratios (M_s/L_V) based on the high-resolution neutral hydrogen (HI) observations of the SMC. We adopt both the Burkert and the NFW profiles for the dark matter halo of the SMC in order to model the radial profile of the observed rotation curve. We show that the mass (M_{dm}) and the mean density (ρ_{dm}) of the dark matter halo within the optical radius (~ 3 kpc) of the SMC can be significantly low for $M_s/L_V = 2 - 4$ reasonable for a galaxy dominated by older stellar populations. For example, the estimated M_{dm} and ρ_{dm} are $7.5 \times 10^7 M_\odot$ and $6.7 \times 10^{-4} M_\odot \text{ pc}^{-3}$, respectively, for $M_s/L_V = 3.8$. The models with lower M_s/L_V (< 1.0) can show higher M_{dm} and ρ_{dm} yet have difficulties in reproducing the inner rotation curve profile both for the Burkert and the NFW profiles. The Burkert profile with a larger core radius (> 1 kpc) (thus a low density) and a large mass ($M_{\text{dm}} > 3 \times 10^9 M_\odot$) can be better fit to the observed slowly rising rotation curve than the NFW one for a reasonable $M_s/L_V \sim 2$. This means that most of the dark halo mass can be initially located outside the optical radius in the SMC and thus that the dark halo would have already lost a significant fraction of its original mass due to the strong tidal interactions with the Galaxy and possibly with the Large Magellanic Cloud (LMC). We suggest that the dark matter halo of the SMC is likely to have the initial total mass and core radius as large as, or larger than, $6.5 \times 10^9 M_\odot$ and 3.2 kpc, respectively. We discuss limitations of the present model in estimating the total mass of the SMC.

Key words: galaxies:dwarf – galaxies:structure – galaxies:kinematics and dynamics – galaxies:star clusters

1 INTRODUCTION

Observational studies of the neutral hydrogen (HI) gas in the Magellanic Clouds (MCs) have played a key role in the understanding of many aspects of their formation, such as the formation of the Magellanic Stream (MS; Mathewson et al. 1974; Putman et al. 1998), gaseous kinematics of the Large Magellanic Cloud (LMC; Staveley-Smith et al. 2003), and the formation of the Magellanic Bridge (MB; Muller et al. 2004). These observations furthermore have attracted much attention from theoretical studies of the roles of LMC-SMC-Galaxy interactions in the formation of the MS (e.g., Murai & Fujimoto 1980), the importance of the last strong LMC-SMC interaction in the formation of the peculiar HI morphology (Bekki & Chiba 2007), and the origin of the bifurcated kinematics in the

MB (e.g., Muller & Bekki 2007). Recent observations of the structural and kinematical properties of the HI gas in the SMC have provided valuable information on the mass distribution of the SMC (Stanimirović et al. 2004, S04).

One of intriguing results by S04 is that the HI gas in the SMC has rotational kinematics with the maximum circular velocity (V_c) of $\sim 60 \text{ km s}^{-1}$. This kinematics is in a striking contrast to the stellar kinematics with no or little rotation (e.g., Harris & Zaritsky 2006), which recently have led Bekki & Chiba (2008) to suggest that the SMC have experienced a major merger event long time ago. Another intriguing result in S04 is that $V_c \sim 60 \text{ km s}^{-1}$, corresponding to the total mass of $2.4 \times 10^9 M_\odot$, can be explained by the mass distribution of baryonic components (i.g., gas and stars) without a dark matter halo for the central 3 kpc: this result however depends strongly on the adopted stellar distribution. These properties certainly make the SMC a highly unusual dwarf galaxy. However, no detailed dynamical studies have been

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Table 1. Parameter values for the representative models.

Model ^a	i (°) ^b	M_S/L_V ^c	M_{dm} (M_\odot) ^d	r_0 (kpc) ^e	r_s (kpc) ^f	c ^g	Comments
NDM1	40	3.8	-	-	-	-	without dark matter halo
NDM2	30	3.8	-	-	-	-	lower inclination angle
NDM3	40	2.3	-	-	-	-	lower M_S/L_V
B1	40	2.3	6.5	3.2	-	-	Burkert profile
B2	40	2.3	79.3	9.5	-	-	
B3	40	0.6	79.3	9.5	-	-	very low M_S/L_V
B4	40	1.0	79.3	9.5	-	-	
NFW1	40	2.3	6.5	-	2.5	10	NFW profile
NFW2	40	2.3	6.5	-	5.1	5	
NFW3	40	2.3	79.3	-	17.7	5	

^a The mass model for the dark matter halo of the SMC: “NDM”, “B”, and “NFW” represent a model with no dark matter (or with no specific dark matter profiles considered), the Burkert profile for the radial density profile of the dark matter halo, and NFW one, respectively.

^b The inclination angles of the gas disk in the SMC.

^c The V-band stellar-to-mass-to-light-ratio.

^d The total mass of the dark matter halo in units of $10^9 M_\odot$.

^e The scale radius in the Burkert profile.

^f The scale radius in the NFW profile.

^g c ($= r_{\text{vir}}/r_s$) parameter in the NFW profile.

conducted to explain the origin of such unusual dark-matter halo.

The purpose of this paper is thus to discuss the existence of dark matter within the central 3 kpc of the SMC, based on the detailed models for the mass distributions of the dark matter halo and the baryonic components. We derive the possible total mass (M_{dm}) and mean density (ρ_{dm}) of the dark matter halo within the optical radius of the SMC required to reproduce the observed HI rotation curve. We discuss whether the modeled distributions of the dark matter halo in the SMC can be consistent with the observed slowly rising rotation curve. We also discuss a possible initial mass of the SMC before the interaction with the Galaxy and the LMC.

This paper focuses on implications and interpretation of observational results presented in S04. We stress that the observed rotation curve of the SMC depends on several adopted parameters: inclination, position angle, the disk thickness and shape of the SMC. In addition, possible radial gas-flows in the SMC, caused by the LMC-SMC-Galaxy interactions, can result in non-circular motions of HI gas and make the estimate of the rotation curve even harder. Some of the adopted parameters can not be directly determined by observations, because the 3D HI structure remains observationally unclear for the SMC. Since observational uncertainties involved in the derivation of the rotation curve have already been discussed in S04, we just briefly summarize them in this paper and explain limitations they impose on the derivation of the dark matter halo. We also point out that the total mass of the SMC derived in S04 agrees well with the estimate based purely on the stellar kinematics (Harris & Zaritsky 2006).

2 POSSIBLE TOTAL MASS AND MEAN DENSITY OF THE DARK MATTER HALO FROM OBSERVATIONS

We first derive the possible mass and density of the dark matter halo of the SMC from the observed rotation curve

(S04) *without using models for the dark matter* in §2.1 and §2.2. We then try to find the density profile of the halo that can fit well to the observed rotation curve using models predicted from previous theoretical studies in §3. We discuss how uncertainties in the observed HI rotation curve (e.g. a possible existence of radial gas inflow) affect our results in Section §2.3.

2.1 The observed rotation curve

Before discussing the possible total mass and density of the dark matter halo of the SMC, we firstly describe the observed radial profiles for the total mass (M) and the rotational velocity (V_c) of each component (e.g., gas and stars) within a distance (R) from the center of the SMC based on the results by S04. We here assume that the SMC has a stellar luminosity of $4.3 \times 10^8 L_\odot$ (i.e., $M_V = -16.76$ mag), which is significantly smaller than that in S04: the rotation curve from stars in the present paper is different from that in S04.

As described in S04, the tilted-ring algorithm was used to derive the HI rotation curve. Keeping the kinematic center fixed, and assuming an inclination angle of 40 degrees, the final rotation curves for the receding and approaching sides of the HI velocity field were derived. As the line-of-sight velocity dispersion in the SMC is high (mean value 22 km s^{-1}), the asymmetric drift correction was applied, resulting in the final rotation curve being higher by about 10 km/sec for $R > 0.5$ kpc than the observed one. In addition, to derive the deprojected rotation curve due to the HI gas alone, an exponential density law was assumed for the vertical HI disk distribution with a scale height of 1 kpc. The deprojected rotation curve due to the stellar component was derived from the surface brightness distribution at V-band. For full details please see S04. Thus the circular velocity (V_c) at a given radius is a combination from dark matter ($V_{c,\text{dm}}$), stars ($V_{c,\text{s}}$), and gas ($V_{c,\text{g}}$). Fig. 1 shows derived radial profiles of M and V_c for the model with the most plausible value for inclination ($i = 40$), $M_S/L_V = 3.8$,

and with no dark matter (referred to as “NDM” model from now on). One source of uncertainty that has not been taken into account previously is the inclination angle. S04 estimated i at each radius and found that the mean value of i is $40^\circ \pm 6^\circ$ within the central 2.3 kpc. After this radius i was found to rise slightly outward. We have hence assumed the observational error (Δi) in i (at a given R) $\Delta = 5^\circ$ and propagated this value to estimate the uncertainty in M and V_c (as shown in Fig. 1). Later, we investigate the models with different *mean* i to infer the minimum and maximum possible masses of the dark matter halo of the SMC within the central 3 kpc.

It is clear that the observed profiles are quite similar to the profiles for the total component (i.e., the combination of stars and gas), though M and V_c around $R = 1 - 2$ kpc for the total component are slightly smaller than the observed ones. Clearly, the observations can be well reproduced without invoking the dark matter halo for the optical radius of the SMC. There is only a slight difference between the total mass (M_t) and the dynamical mass estimated from V_c within the central 3 kpc. If this difference is due to the presence of the dark matter halo, the total mass (M_{dm}) and the mean density (ρ_{dm}) within the central 3 kpc are $7.5 \times 10^7 M_\odot$ and $6.7 \times 10^{-4} M_\odot \text{ pc}^{-3}$, respectively.

What would be a reasonable value for M_s/L_V based on integrated optical colors? We use the formulae described by Bell & de Jong (2001, BD01) and the observed colors of the SMC: $B - V (=0.41)$ and $B - R (=0.70)$. If we use the low metallicity models with $Z = 0.008$ in BD01, the most plausible M_s/L_V is about 1. However, M_s/L_V can range from 0.6 to 1.0 for different stellar population models and star formation histories (BD01, S04). The stellar population synthesis models for $[\text{Fe}/\text{H}] = -0.68$ and ages of 2, 10, and 13 Gyr by Vazdekis et al. (1996) show $M_s/L_V = 1.1, 3.8,$ and 4.4 respectively. This means that M_s/L_V strongly depends on the luminosity-weighted age of the stellar populations. As it is observationally not clear what are the dominant ages of stellar populations, we assume that M_s/L_V is a free parameter in the present study. Given that the SMC contain a significant fraction of older stellar populations (Harris & Zaritsky 2004), we consider that the reasonable M_s/L_V would be 2–4 for the observed large fraction of old stars in the SMC (e.g., Harris & Zaritsky 2004).

2.2 Uncertainties in M_s/L_V and i

We now explore how M_s/L_V and i affect M_{dm} and ρ_{dm} . Generally, for a given M_s/L_V , $i < 40$ degrees results in significantly larger M_{dm} and ρ_{dm} . We first calculate M_{dm} from the total mass (derived from the observed V_c at $R = 3$ kpc for a given i) and the observed gaseous (M_g) and stellar masses (M_s) for a given M_s/L_V : $M_{\text{dm}} = M - M_g - M_s$ so that no cold and warm gas possibly in the SMC’s halo can be considered. We then estimate ρ_{dm} from the derived M_{dm} within the central 3 kpc of the SMC. Fig. 2 shows that M_{dm} and ρ_{dm} are significantly smaller than M_b (i.e., the total mass of the baryonic components including both gas and stars) and ρ_b (the mean density of the baryonic components), respectively, for a reasonable $i (= 40^\circ)$ and $1.5 \leq M_s/L_V \leq 3.8$. Only if i is largely underestimated by $\sim 10^\circ$ in the observation by S04, M_{dm} and ρ_{dm} can be significantly large: the model NDM2 with $i = 30^\circ$ shows

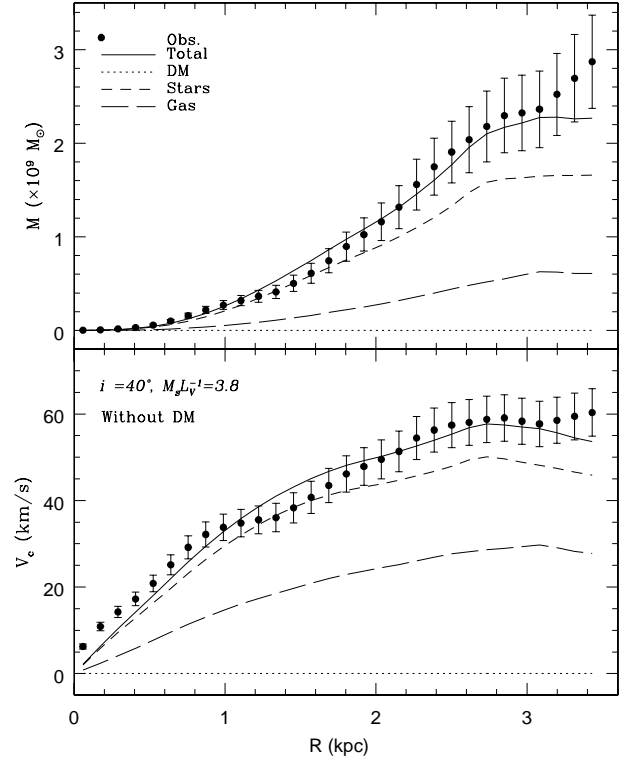


Figure 1. The total masses (M , upper) within R (where R is the distance from the center of the SMC) and circular velocities (V_c , lower) at R for all components (solid), dark matter (DM) one (dotted), stellar one (short-dashed), and gaseous one (long-dashed) in the model NDM1 without dark matter. Here the inclination angle i and the V -band stellar-to-mass-to-light-ratio (M_s/L_V) are 40° and 3.8, respectively. For comparison, the observed values are plotted by filled circles.

$M_{\text{dm}} = 1.6 \times 10^9 M_\odot$ and $\rho_{\text{dm}} = 0.015 M_\odot \text{ pc}^{-3}$. Since i is determined by the tilted ring algorithm at each R in S04, it is unlikely that i is underestimated by $\sim 10^\circ$ for the entire region of the SMC. We thus conclude that the larger M_{dm} due to the smaller i is highly unlikely.

It should be stressed here that (i) the derived total mass of $2.4 \times 10^9 M_\odot$ for the best $i (= 40^\circ)$ in S04 is consistent with that derived from stellar kinematics of the SMC (e.g., Harris & Zaritsky 2006) and (ii) the best i is also consistent with that for the best theoretical model that can explain physical properties of the Magellanic Stream and Bridge (e.g., Yoshizawa & Noguchi 2003). These strongly suggest that although i and position angles change with R in S04, the best i and position angle in S04 can be very close to the true ones. This implies that the adopted tilted-ring algorithm in S04 is still useful in accurately estimating the rotation curve for the inner part of the SMC ($R < 3$ kpc), where the influences of the LMC-SMC-Galaxy interaction can be relatively weak.

The model NDM3 with $M_s/L_V = 2.3$ shows $M_{\text{dm}} = 7.8 \times 10^8 M_\odot$ and $\rho_{\text{dm}} = 6.9 \times 10^{-3} M_\odot \text{ pc}^{-3}$. M_{dm} and ρ_{dm} are smaller for a larger M_s/L_V : M_{dm} and ρ_{dm} are $4.3 \times 10^8 M_\odot$ and $3.8 \times 10^{-3} M_\odot \text{ pc}^{-3}$, respectively, for $M_s/L_V = 3.1$. The total mass of the dark matter halo within the optical radius of the SMC in the model NDM3 is, however, still low, given that the total baryonic mass of the

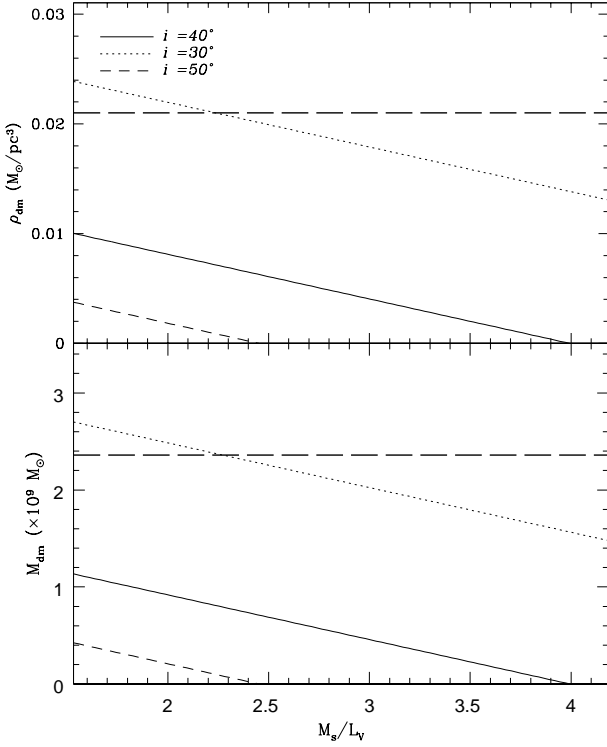


Figure 2. The mean density (ρ_{dm} , upper) and the total mass (M_{dm} , lower) of the dark matter halos within the central 3 kpc of the SMC as a function of M_s/L_V , for $i = 40^\circ$ (solid), $i = 30^\circ$ (dotted), and $i = 50^\circ$ (dashed). For comparison, the mean density (ρ_{dm}) and the total mass (M_b) for the baryonic component of the SMC for $M_s/L_V = 3.8$ are shown by dashed lines. This figure indicates the possible upper and lower masses of the SMC dark matter halo.

SMC is $1.6 \times 10^9 M_\odot$. The SMC may well be a baryon-dominated dwarf galaxy. These results imply that only if the SMC is dominated by a very young stellar population, and thus has a small M_s/L_V , the SMC can have a certain amount ($\sim 10^9 M_\odot$) of dark matter within its optical radius.

As a conclusion, the SMC can contain a certain amount of dark matter within its optical radius, if it has a significant fraction of young stellar populations and thus a small M_s/L_V (~ 0.6): M_{dm} and ρ_{dm} depend strongly on M_s/L_V such that they are both larger for smaller M_s/L_V for a given i . The SMC can hardly contain dark matter, if it is dominated by old stellar populations with ages larger than 10 Gyr and thus has $M_s/L_V \geq 4$. In the next section, we discuss possible mass distributions for the SMC's dark matter halo that can be fitted to the observed V_c profile by assuming $M_s/L_V = 2.3$ (corresponding to ages of stellar populations similar to 5 Gyr) that would be reasonable for a galaxy having a large fraction of older stellar populations like the SMC.

2.3 Limitations of the mass estimation

We have so far considered that the observed rotation curve is very close to the true one with some possible uncertainty of the disk inclination (i). It should be here stressed that the observed rotation curve can be slightly different from the true one owing to the possible non-circular flow of gas caused by the presence of a stellar bar in the SMC. The latest

survey of 2046 red giant stars has suggested that the older stellar components of the SMC have a velocity dispersion (σ) of $\sim 27.5 \text{ km s}^{-1}$ and a maximum possible rotation of $\sim 17 \text{ km s}^{-1}$ (Harris & Zaritsky 2006). The older stars are observed to have a more regular distribution and appear to be a slightly flattened ellipsoid rather than a disk (e.g., Cioni et al. 2000). These implies that the SMC has a stellar spheroid rather than a rotating disk: the SMC is unlikely to have a bar composed of older stars. The lack of a stellar bar would not cause the non-circular motion of gas in the SMC and thus suggests that the observed rotation curve by S04 is highly unlikely to be influenced by the non-circular motion of gas due to the bar.

As discussed by S04, numerous expanding shells in the SMC can provide some non-circular motions and thus be the main reason for the possible non-perfect rotation curve of the SMC. S04 however considered this effect (i.e., introduction of velocity dispersion) by calculating the asymmetric drift correction. The last LMC-SMC tidal interaction about 0.2 Gyr can give tidal perturbation to the SMC and thus influence gas dynamics of the SMC in its outer part (Bekki & Chiba 2007). Although the outer part of gas ($3 < R < 5 \text{ kpc}$) can be stripped to form the Magellanic Bridge during the interaction (e.g., Yoshizawa & Noguchi 2003; Muller & Bekki 2007), the inner part of the present SMC (i.e., 0.2 Gyr after the last interaction) can still show clear rotation. Therefore, if the disordered gas motion due to the last LMC-SMC interaction can influence the present mass estimation of the SMC from the observed rotation curve, the influence would be significantly small: a possible influence would be slight underestimation of the mass due to V_c smaller than the true value resulted from a higher velocity dispersion (caused by the last interaction) in the outskirts of the SMC.

The 3D structure (e.g., thickness and shape) of the HI gas in the SMC remains observationally unclear. We thus can not make robust conclusions on how the thickness and shape of the HI can influence the mass estimation of the SMC. S04 adopted a reasonable assumption on a constant vertical scale-height (1 kpc) and considered asymmetric drift corrections in deriving the rotation curve of the SMC. We here suggest that a possible large intrinsic ellipticity (e.g., $\epsilon \sim 0.3$) of the HI distribution can introduce an observational error in the estimation of the rotation curve in the SMC. Since the possible range of ϵ for the SMC is observationally unclear, it is hard for the present study to make a quantitative estimation for the possible observational error. Keeping these limitations in mind, we discuss the models for the dark matter halo of the SMC in the following sections.

3 THE MODELS FOR THE DARK MATTER HALO

3.1 The NFW profile

We now investigate the M - and V_c -profiles in the models with dark matter halos and $M_s/L_V = 2.3$ reasonable for the SMC having a large fraction of intermediate-age and old stellar populations. We adopt the same radial density profiles (described later) of dark matter halos as widely adopted in other studies (on isolated systems with no apparent galaxy interaction), though the SMC appears to be interacting with

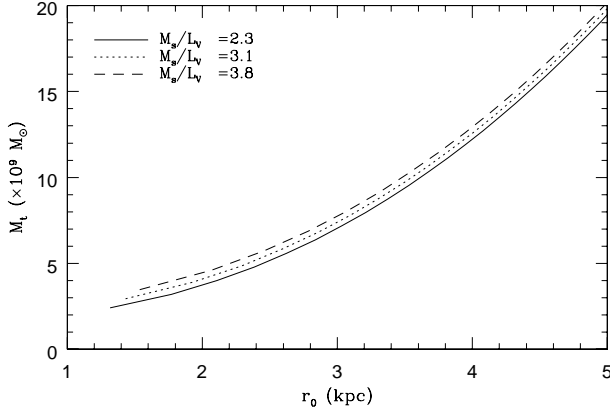


Figure 3. The relation between the core radius (r_0) of the SMC's dark matter halo described as the Burkert profile (B95) and the total mass of the SMC (M_t) for $M_s/L_V = 2.3$ (solid), $M_s/L_V = 3.1$ (dotted), and $M_s/L_V = 3.8$ (dashed).

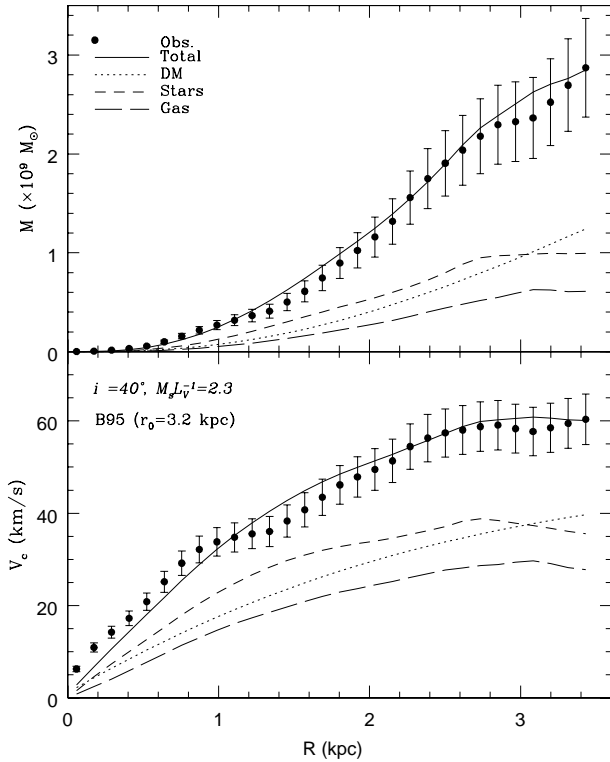


Figure 4. The same as Fig. 1 but for the model B1 in which the Burkert profile with $r_0 = 3.2$ kpc, $i = 40^\circ$, and $M_s/L_V = 2.3$ are adopted. M_{dm} and M_t are $6.5 \times 10^9 M_\odot$ and $8.1 \times 10^9 M_\odot$, respectively, in this model. Note that the Burkert profile with a large core radius can well reproduce the slowly rising V_c profile.

the LMC and the Galaxy. We think that this adoption can be reasonable, because we discuss the density profile in the inner part of the dark halo, where the influence of the Galaxy-LMC-SMC interaction is relatively small.

We adopt the following two profiles for the radial density distribution of the dark matter halo of the SMC: the “NFW” profile with a central cusp predicted from hierarchical clustering scenarios based on the cold dark matter

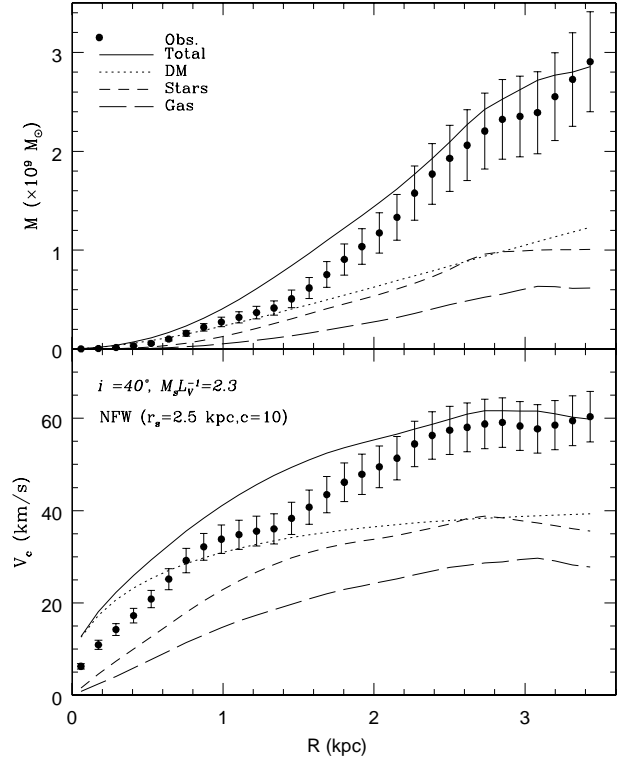


Figure 5. The same as Fig. 1 but for the model NFW1 in which the NFW profile with $r_s = 2.5$ kpc and $c = 10$, $i = 40^\circ$, and $M_s/L_V = 2.3$ are adopted. M_{dm} and M_t are exactly the same as those used in the Burkert one shown in Fig. 4. Note that the fit of the NFW profile to the observation is worse than the Burkert profile in Fig. 4, though the NFW profile can better reproduce the V_c profile in the outer part ($R \sim 3$ kpc).

models (Navarro et al. 1995) and the “Burkert” profile with a flat “core” (Burkert 1995; B95).

The NFW profile is described as:

$$\rho_{dm}(r) = \frac{\rho_0}{(r/r_s)(1+r/r_s)^2}, \quad (1)$$

where r , ρ_0 , and r_s are the distance from the center of the cluster, the scale density, and the scale-length of the dark halo, respectively. The ratio of the virial radius (r_{vir}) and r_s is a parameter in the NFW profile and described as c . A dark matter halo with the total mass of $6.5 \times 10^9 M_\odot$ and $c = 10$ has $r_s = 2.5$ kpc and the virial velocity of 33 km s^{-1} in the NFW profile. The total mass in a NFW model is defined as the mass within r_{vir} in the present study.

3.2 The Burkert profile

The Burkert profile is described as:

$$\rho_{dm}(r) = \frac{\rho_{dm,0}}{(r+r_0)(r^2+r_0^2)}, \quad (2)$$

where $\rho_{dm,0}$ and r_0 are the central dark matter density and the core (scale) radius, respectively. In the Burkert profile (B95), a relation between the total mass within the core (M_0) and r_0 is described as:

$$M_0 = 7.2 \times 10^7 \left(\frac{r_0}{1 \text{ kpc}} \right)^{-7/3} M_\odot. \quad (3)$$

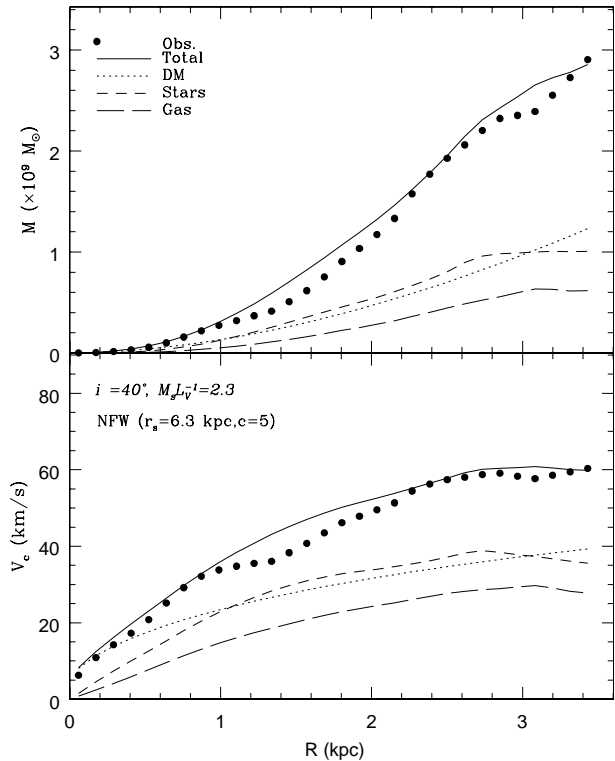


Figure 6. The same as Fig. 1 but for the model NFW3 in which the NFW profile with $r_s = 17.7$ kpc and $c = 5$, $i = 40^\circ$, and $M_s/L_V = 2.3$ are adopted. In this model, unusually large mass and low density of the dark matter halo for the SMC are assumed just for comparison with the results shown in Fig. 4 and 5.

The virial radius (R_h) and the total mass of the dark matter halo in this profile are equal to $3.4 \times r_0$ and $5.8 \times M_0$, respectively. Therefore the total mass of the dark matter halo within R_h in the SMC can determine the core radius (r_0). Fig. 3 shows a relation between r_0 and $M_t (= M_{\text{dm}} + M_b)$ derived from the equation (3) for three different M_s/L_V . The parameter values (e.g., r_s and r_0) of models that are investigated in detail are summarized in the Table 1.

The tidal radius of the SMC is about 5 kpc (Gardiner & Noguchi 1996) so that the shape of the dark matter halo can keep its (assumed) spherical shape within the central 3 kpc after the LMC-SMC interaction. Therefore, the assumed spherically symmetric distribution of the dark matter halo in both the NFW and Burkert profiles can be regarded as reasonable even for the SMC about 0.2 Gyr after the last strong interaction with the LMC.

3.3 Comparison with observations

Fig. 4 shows that the model B1 having the Burkert profile with $M_{\text{dm}} = 6.5 \times 10^9 M_\odot$ and $r_0 = 3.2$ kpc (i.e., $M_t = 8.1 \times 10^9 M_\odot$ and $R_h = 11.0$ kpc) can well reproduce observations in terms of both (i) the slowly rising V_c profile in the inner part ($R < 2$ kpc) and (ii) the maximum V_c (~ 60 km s $^{-1}$). The total mass of the dark matter halo within 3 kpc is about $10^9 M_\odot$, which is still smaller than the total baryonic mass. These results imply that the SMC can have a large core in the mass distribution of the dark matter halo. We confirm that more massive models (e.g., B2) with larger r_0 can also

reproduce well the observed V_c profile. The results of the models with lower M_s/L_V ($=0.6$ and 1) are shown in the Appendix A for comparison.

Fig. 5 shows the simulated V_c as a function of R for the model NFW1 having the NFW profile with $c = 10$, $r_s = 2.5$, and M_{dm} being exactly the same as that used in the Burkert profile shown in Fig. 4. It is clear that although the NFW profile can reproduce the maximum V_c around $R \sim 3$ kpc, it can not fit to the observed V_c profile as well as the Burkert one. In particular, in the central region ($R < 2$ kpc) the simulated profile is systematically well above the observed data points. The higher mass-density in the inner region of the dark matter halo described in the NFW profile is responsible for this discrepancy. These results imply that the NFW profile with reasonable model parameters are highly unlikely to reproduce the observations.

It should be however stressed that an unusually low-density (i.e., smaller c), high-mass dark matter models with the NFW profile can reproduce the observations as well as the Burkert profiles. For example, the simulated V_c profile in the model NFW2 with $M_{\text{dm}} = 6.5 \times 10^9 M_\odot$, $c = 5$, and $r_s = 5.1$ kpc can be well consistent with the observations. Fig. 6 shows the simulated V_c profiles for the model NFW3 with $M_{\text{dm}} = 7.9 \times 10^{10} M_\odot$, $c = 5$, and $r_s = 17.7$ kpc. In this extreme example with a low-density dark matter halo, the observations can be well reproduced, although it is unlikely that the mass of the SMC is much larger than that of the LMC ($\sim 2 \times 10^{10} M_\odot$) that was previously considered to form a binary with the SMC (e.g., Murai & Fujimoto 1980).

These results imply that the Burkert profile is better than the NFW one in terms of reproducing HI rotation curve in the SMC. Although these results do not rule out the NFW profile for the distribution of the dark matter halo of the SMC, the observed low-density dark matter halo (or large central concentration of the baryonic components) needs to be explained in the context of hierarchical clustering scenarios. If, however, the SMC has such a large initial mass of $M_{\text{dm}} = 7.9 \times 10^{10} M_\odot$, as shown in Fig. 6, then our views of the formation and evolution processes in the Magellanic system can be dramatically changed.

4 DISCUSSION

4.1 A massive past of the SMC

If the SMC has low-mass and low-density of the dark matter, as shown in our models, then the present results have the following four implications. Firstly, the SMC could have lost most of its original mass through tidal interactions with the Galaxy and the LMC owing to the extended initial distribution of the dark matter halo. Essentially, the present-day SMC is a stripped core of an initially much larger galaxy. The SMC's tidal radius (r_t) against the Galaxy can range from 5 kpc to 7.5 kpc for the total mass (M_t) of $3 - 10 \times 10^9 M_\odot$ (see the formula for the mass estimate in Gardiner & Noguchi 1995). Therefore R_h (11 kpc) for the SMC with $M_{\text{dm}} = 6.5 \times 10^9 M_\odot$ is significantly larger than r_t , which means that the SMC could have lost all components outside r_t owing to tidal stripping. The stripped matters may well be now observed as the MS, the MB, and the stream of dark matter in the outer halo of the Galaxy.

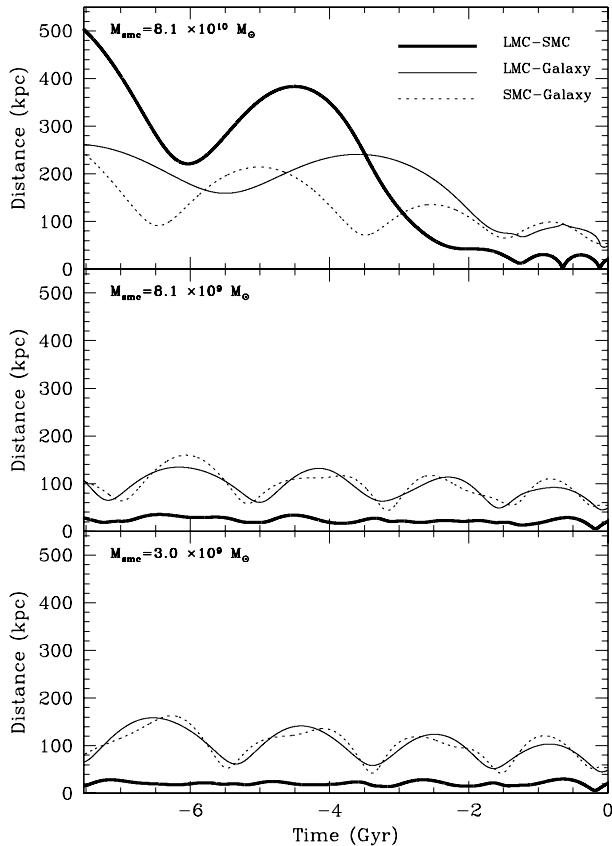


Figure 7. Orbital evolution of the MCs for $M_{\text{smc}} = 8.1 \times 10^{10} M_{\odot}$ (top), $M_{\text{smc}} = 8.1 \times 10^9 M_{\odot}$ (middle), and $M_{\text{smc}} = 3.0 \times 10^9 M_{\odot}$ (bottom). The time evolution of distances between MCs (thick solid), the LMC and the Galaxy (thin solid), and the SMC and the Galaxy (dotted) are separately shown. Here the total mass of the LMC is assumed to be $2.0 \times 10^{10} M_{\odot}$.

Secondly, the SMC could have much more strongly influenced the LMC owing to its larger mass, in particular, for the last 3 Gyrs. The previous models assumed that $M_t \sim 3 \times 10^9 M_{\odot}$ (e.g., Gardiner & Noguchi 1995; Yoshizawa & Noguchi 2003; Bekki & Chiba 2005, BC05), which thus would have underestimated gravitational influences of the SMC on the LMC. Thirdly, the SMC may well initially have a larger amount of HI gas owing to its large total mass. The total gas mass of the SMC in previous MS models is limited to less than $10^9 M_{\odot}$ owing to the adopted models with smaller M_t (e.g., Yoshizawa & Noguchi 2003). This limitation was responsible for the less consistent model for the total mass of the MS and the MB (Yoshizawa & Noguchi 2003). Thus if future theoretical works adopt a more massive SMC model, they will much more consistently explain the observed total mass ($> 10^9 M_{\odot}$) of the MS and the MB.

Fourthly, future orbital evolution models for the MCs would need to be revised significantly by considering the possible large total mass of the SMC. Since the orbital evolution of the MCs, which strongly depends on the mass of the SMC, is the most important ingredient for the formation of the MS and the MB (e.g., Yoshizawa & Noguchi 2003; Muller & Bekki 2007), the models with larger M_t can describe the formation processes in a quite different manner:

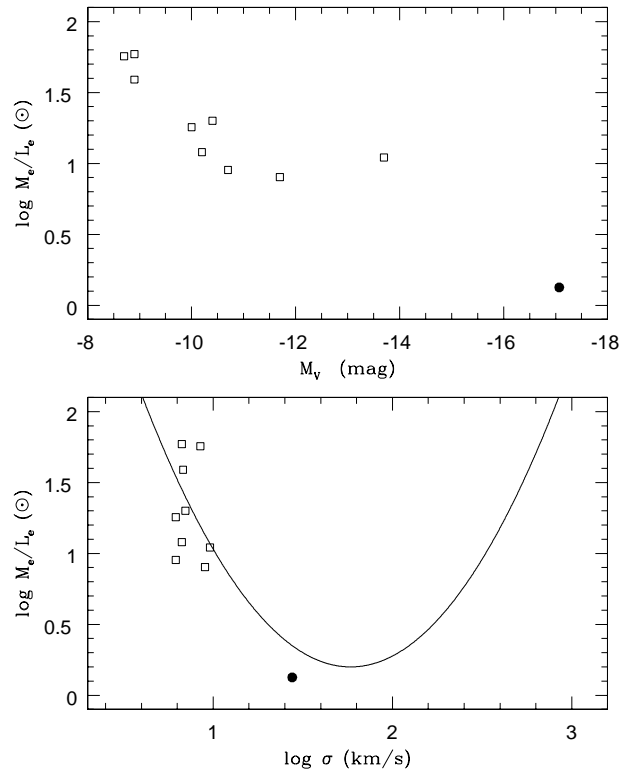


Figure 8. The dependences of M_e/L_V on M_V (upper) and on σ (lower) within effective radii for the dwarfs in the Local group (open squares) and the SMC (filled circles). Here M_e and σ represent the total masses (including dark matter halos) within effective radii and velocity dispersions for dwarfs, respectively. Here the observational results by Mateo (1997) are used and the solid line in the lower panel is from Zaritsky et al. (2006).

future theoretical works on the MS and MB formation need to investigate models with a larger initial mass of the SMC.

In order to illustrate how the orbital evolution of the MCs can be changed owing to a larger mass of the SMC, we investigate the evolution based on the same orbital evolution model used in previous works (e.g., BC05): the adopted initial parameters on initial positions and velocities of the MCs and the gravitational potential of the Galaxy are exactly the same as those in BC05. Fig. 7 shows the orbital evolution of the MCs for the models in which (i) the methods to model orbital evolution of the MCs are the same as those used in BC05 as “no dynamical friction”, and (ii) $M_t (= M_{\text{smc}})$ is equal to or much larger than that used in BC05 ($3 \times 10^9 M_{\odot}$). It is clear from this figure that even if dynamical friction between the MCs is not included, the MCs can not keep their binary status for more than a few Gyrs in the model with large M_t . We confirm that if the SMC has $M_t > 1.5 \times 10^{10} M_{\odot}$, the MC can not keep its binary status for more than 4 Gyrs.

If dynamical friction between the MCs can be effective, the MCs can not keep their binary status for more than 4 Gyrs even for $M_t = 3 \times 10^{10} M_{\odot}$ (BC05): the more massive SMC suggested in the present study is highly unlikely to be coupled with the LMC for more than 4 Gyrs. Furthermore, the evolution processes (e.g., star formation history) of the SMC can be significantly different in the models with larger M_t owing to the stronger self-gravity of the SMC against

tidal perturbations from the Galaxy and the LMC. Thus HI observations on the mass distribution of the SMC (e.g., S04) may well change significantly views about formation and evolution of the MCs.

Sofue (1998) analyzed the rotation curve profile of M82 and found that the profile declines in a Keplerian fashion outside 200 pc. He thus suggested that (i) a significant amount of mass is missing in the outer part of M82 and (ii) tidal stripping due to past tidal interaction between M81 and M82 is responsible for the missing mass. These results by Sofue (1998) and the present ones suggest that the SMC would be the second case of low-mass galaxies that have lost a significant fraction of their original masses. A significant difference between these two galaxies is that the rotation curve of the SMC is not observed to show a decline in a Keplerian fashion even for the outer part.

4.2 The closest dIrr or dSph with a flat DM core

The present study has first suggested that the dark matter halo of the SMC has a flat core well described by the Burkert profile rather than the NFW one: the SMC can be the nearest example of dIrr's (or dSph's) in which the NFW profiles are hard to fit to HI rotation curves. It should be however stressed that Valenzuela et al. (2007) have recently suggested a possibility of a large underestimate of the HI rotational velocity in the central 1 kpc region of two dwarf galaxies due to noncircular motions. Since Valenzuela et al. (2007) adopted rotating disk models for their investigation, their results can not be applied directly to the SMC which has no evidence of stellar rotation (Harris & Zaritsky 2006).

However, if the last close LMC-SMC interaction (Bekki & Chiba 2007) could cause the radial flow of HI gas and thus the noncircular motions, then the observed V_c in S04 could be underestimated. If this is the case, the NFW profile with a cuspy core would be still possible. The present models are not based on numerical simulations of HI gas in the SMC thus can not allow us to make it clear whether the underestimation of circular velocities suggested by Valenzuela et al. (2007) is equally possible in the gas disk of the SMC interacting with the Galaxy and the LMC. We plan to discuss this problem in our future paper in which the HI rotation curve of the SMC will be constructed based on hydrodynamical simulations of the SMC evolution.

The derived small mass of the dark matter halo within the optical radius of the SMC suggests that the SMC is a baryon-dominated galaxy. This strong central concentration of baryonic components in the SMC also suggests that the formation history of the SMC can be significantly different from that of other dIrr's dominated by dark matter halos. Fig. 8 shows how unique the SMC is by comparing the location of the SMC and dwarfs in the Local group on the $M_V - M_e/L_V$ plane and $\sigma - M_e/L_V$ one, where M_e and σ represent the total masses (including dark matter halos) within effective radii and velocity dispersions, respectively. Although the SMC has much lower M_V/M_e in comparison with other dwarfs in the Local group, it is possible that M_V/M_e is not so low for a luminous dwarf population (i.e., more luminous dwarfs can have lower M_V/M_e ; see Zaritsky et al. 2006).

If the SMC really has a very low-density dark matter halo and thus a strong concentration of its baryonic compo-

nents within the central 3kpc, then the origin of this unique nature of the SMC needs to be understood. Efficient transfer of gas to the central regions of galaxies and the resultant starbursts there in galaxy merging (e.g., Mihos & Hernquist 1995) may significantly increase the baryonic fractions of merger remnants. Recently, Bekki & Chiba (2008) have suggested that the SMC was formed from merging of two gas-rich dIrr's with extended HI gas very long time ago. Therefore, the observed large fraction of baryonic component in the SMC can be due mainly to the past major merger event that formed the SMC. Thus the observed HI kinematics of the SMC can provide unique insights into the formation history of the SMC.

4.3 Stronger constraints on the mass of the SMC from future observations

One of potential problems in estimating the mass of the SMC based on the observed V_c profile is that we can underestimate significantly the SMC's inclination angle (e.g., by 20 degrees in i). The HI distribution and kinematics are highly disturbed by numerous expanding shells (S04), making a more accurate estimate of the inclination angle very difficult. A significant underestimate of the inclination angle, although highly unlikely, would result in a larger total mass of the SMC within the central 3 kpc (e.g., $5.3 \times 10^9 M_\odot$ for the true V_c of 80 km s^{-1}). Therefore, future observations of the distribution and radial velocities of a large number of older stars (e.g., RGB and AGB stars) are very important to derive the mass of the SMC independently from the HI observations (S04).

Although the present study has shown that the SMC can have a small amount of dark matter within the central 3 kpc, the detailed profile of the dark matter distribution in the SMC has not been determined. The observed V_c profile within the central 3 kpc alone does not allow us to distinguish between the Burkert model with $M_t \sim 6.5 \times 10^9 M_\odot$ and a very massive Burkert (or even NFW) profile with $M_t > 10^{10} M_\odot$. The mass profile of the SMC at $R > 3 \text{ kpc}$, where less massive models can show almost flat V_c profiles, need to be observationally investigated to provide stronger constraints on the distribution of the dark matter halo in the SMC.

Noël & Gallart (2007) have recently found intermediate-age and old stars belonging to the SMC but being located 6.5 kpc from the SMC center. This suggests that the SMC stellar population may be more massive than previously thought. Future spectroscopic observations of radial velocities of the stars in the outer halo will enable us to derive the mass profile for the outer regions of the SMC and thus to better constraint the radial mass profile of the dark matter halo. The ongoing VMC project (the VLT VISTA near-infrared YJK_s survey for the MCs), combined with other large projects, will soon provide structural and kinematical data sets for the outer regions of the SMC (e.g., Cioni et al. 2007). We plan to discuss the entire mass profile of the dark matter halo of the SMC based both on these ongoing observations and previous HI observations (S04) in our future papers.

5 CONCLUSIONS

We have investigated the mass (M_{dm}) and the mean density (ρ_{dm}) of the dark matter halo within the optical radius (~ 3 kpc) of the SMC based on the high-resolution HI observations of the SMC. Although there are some limitations of the present models in estimating the total mass of the SMC solely from the observed HI rotation curve by S04, we have tried to derive the mass and best possible dark matter models. The results and their implications are described as follows.

(1) The total mass, mean density, and distribution of the dark matter halo depend strongly on the adopted M_s/L_V . For example, the estimated M_{dm} and ρ_{dm} are $7.5 \times 10^7 M_\odot$ and $6.7 \times 10^{-4} M_\odot \text{ pc}^{-3}$, respectively, for $M_s/L_V = 3.8$. This implies that if the SMC is dominated by older stellar populations, the SMC has a low-density dark matter halo described by B95 rather than by the NFW.

(2) The models with lower M_s/L_V (< 1) can show higher M_{dm} and ρ_{dm} yet have difficulties in reproducing the observed rotation curve, in particular, the inner part ($R < 1$ kpc) of the curve, both for the Burkert and the NFW profiles. This implies that the SMC is unlikely to be dominated by younger stellar populations.

(3) The Burkert profile can fit better the observed HI rotation curve of the SMC than the NFW profile for a reasonable M_{dm} and M_s/L_V for reasonable M_s/L_V (~ 2). However the NFW profiles with low-densities, small c (~ 5), and large total masses ($M_{\text{dm}} > 10^{10} M_\odot$) can be also fit well the observations, though such low-density NFW profiles are highly unlikely for low-mass dwarfs like the SMC. The SMC can be the closest example among dIrr's in which rotation curves are difficult to fit to the mass profiles of dark matter halos predicted by hierarchical clustering models.

(4) The dark matter halo of the SMC is likely to have the initial total mass of $M_{\text{dm}} \sim 6.5 \times 10^9 M_\odot$ and the core radius of $r_0 \sim 3.2$ kpc, which means that the SMC could be much more massive than what was previously thought.

(5) Orbital evolution models of the SMC and the LMC, on which formation models of the MS and the MB are based, would need to be revised by considering the derived much larger total mass of the SMC. The observed large concentration of the baryonic components in the SMC is due to its unique formation history and is very different from those of other dIrr's.

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APPENDIX A: THE MODELS WITH LOWER MASS-TO-LIGHT-RATIOS

The models with lower M_s/L_V (i.e., smaller stellar masses) have larger masses of the dark matter halo and thus larger core (or scale) radii for the SMC. It would be therefore interesting to discuss whether such more massive models can explain the *inner part* of the observed rotation curve. Fig. A1 shows that for $M_s/L_V = 0.6$, even the very massive dark matter model (B3) with $r_0 = 9.5$ kpc (corresponding to $M_{\text{dm}} = 7.9 \times 10^{10} M_\odot$) with the Burkert profile can not explain the observed profile of the rotation curve owing to the required large mass in the inner region of the SMC. Fig. A2 also shows that for $M_s/L_V = 1.0$, the massive model (B4) can not reproduce the inner part of the observed rotation curve owing to the low density of the halo. It should be stressed here that the SMC is highly unlikely to have a mass much larger than that of the LMC ($\sim 2 \times 10^{10} M_\odot$).

These results imply that in order for the observed rotation curve to be reproduced by the present model, a higher M_s/L_V needs to be adopted: the SMC is highly unlikely to be dominated by younger stellar populations. This is consistent with the results by Harris & Zaritsky (2004) who

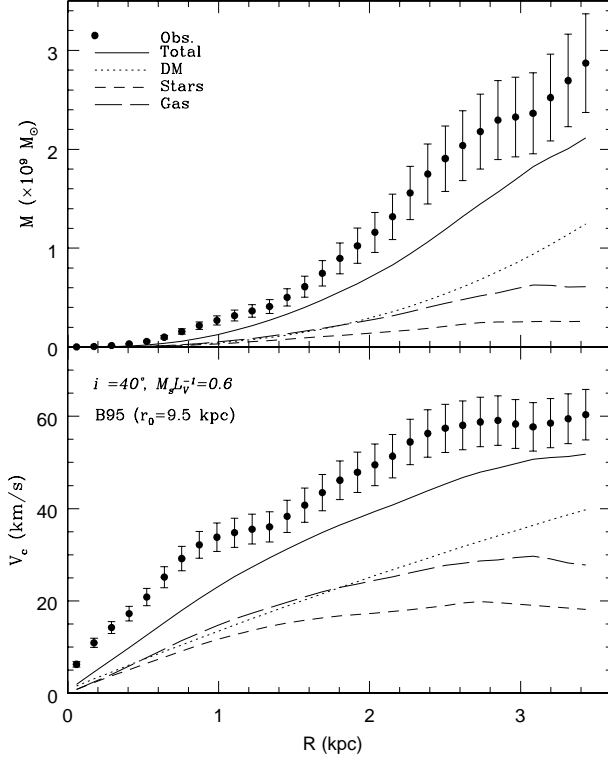


Figure A1. The same as Fig. 1 but for the model B3 in which the Burkert profile with $r_0 = 9.5$ kpc, $i = 40^\circ$, and $M_s/L_V = 0.6$ are adopted ($M_{\text{dm}} = 7.9 \times 10^{10} M_\odot$).

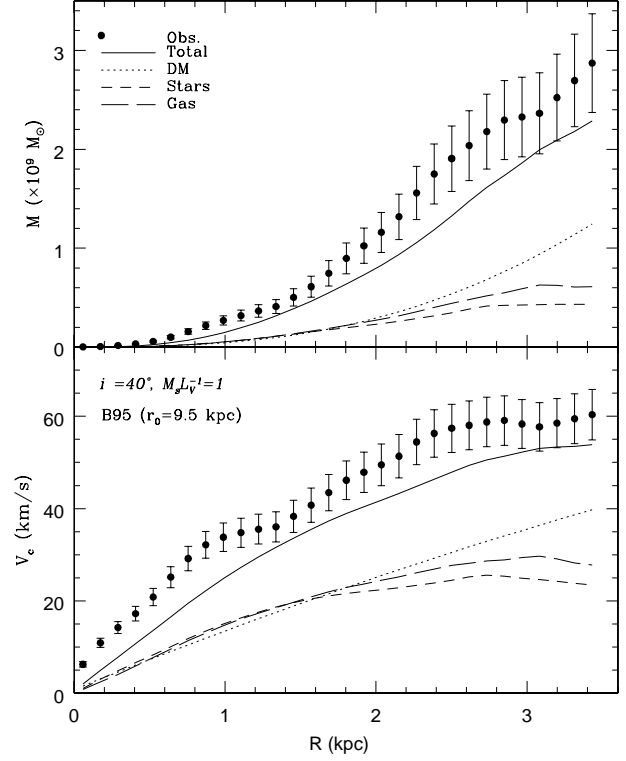


Figure A2. The same as Fig. 1 but for the model B4 in which the Burkert profile with $r_0 = 9.5$ kpc, $i = 40^\circ$, and $M_s/L_V = 1$ are adopted ($M_{\text{dm}} = 7.9 \times 10^{10} M_\odot$).

showed that about 50% of the stellar populations in the SMC were formed prior to 8.4 Gyr ago. Given that the large fraction of stars in the SMC are suggested to be formed between 2.5 and 3 Gyr ago in starbursts (Harris & Zaritsky 2004), the SMC must be dominated by intermediate-age and old stellar populations. Thus we can conclude that our successful reproduction of observations in the models with higher $M_s/L_V \sim 2 - 4$ is quite reasonable.